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ENERGY BUDGET AND GROUND TEMPERATURES IN HOT REGIONS

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This report discusses characteristics of the atmospheric energy balance which contribute to the production of high surface air temperatures and high ground temperatures. This discussion is followed by climatological information. The hottest regions are in northwestern Africa, the Arabian Peninsula, part of Pakistan, and a small part of the southwestern United States.

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I. INTRODUCTION

Energy transfer in the atmosphere and at the interface of the air and the solid earth (or an object on the earth) is very complex. According to basic physics, energy is transferred from one place to another by conduction, convection, and radiation [1]. The meaning of convection here is not the specialized meaning often used in meteorology to refer to predominantly vertical motion. In general, convection means mass motion within a fluid resulting in transport and mixing of properties of the fluid. Each of the three methods of energy transfer has considerable small-scale variation.

Both solar and terrestrial radiation are attenuated by the atmosphere. Solar energy is absorbed primarily by oxygen, ozone, water vapor, and nitrogen compounds. Longer wavelength terrestrial radiation is absorbed by water vapor, carbon dioxide, and numerous pollutants. The percentage of oxygen in the air is not highly variable in the lower atmosphere. Concentrations of water vapor may be computed from temperatures and dew points. Accurate measurements of other absorbing molecules are not available at most sites. Droplets and solid particles scatter and absorb large amounts of energy in the visible and infrared portions of the electromagnetic spectrum. Size distributions and indices of refractions which vary with wavelength are needed to compute atmospheric attenuation by droplets and particles. Estimates of sizes must be used in these computations because these are not regularly measured.

The amount of electromagnetic energy reflected at the surface is seldom negligible. The ratio of the amount of electromagnetic energy reflected by a surface to the amount incident upon it is called the albedo [2]. The average total albedo of solar radiation for the entire earth-atmosphere system has been estimated from approximately 30 to 50 percent [3, 4]. Estimates of the mean planetary albedo for only the visible portion of the spectrum are also usually in this range.

Thermal conductivity of the soil near the surface is often an important factor in the heat budget.

Energy can be transported from one place to another by mean air motion or by turbulent motion. Net transfer of heat by turbulent fluctuations in the atmosphere is not known with precision at most sites. Some information about mean horizontal motion can be obtained from wind observations reported in standard meteorological data.

Vertical motion not only transfers energy but also causes changes in temperature by means of adiabatic processes. Parcels of air which are transported vertically experience expansion or compression because of changes in pressure. The associated temperature changes are sometimes very important.

This report describes how the different methods of energy transfer combine to produce observed temperatures of the ground and objects on the surface. Primary concern is with combinations which produce high temperatures. Climatological information about very hot regions is discussed.

II. RADIATION

A. Solar Radiation

The sun radiates approximately as a black body with a temperature near 5700°K. The wavelength of maximum intensity is near 0.47 μm, and 99.9 percent of the energy is within the range 0.15-4.0 μm [2]. Roughly half of solar radiation is within the visible limits 0.4-0.7 μm.

The rate at which solar energy is received outside the atmosphere at the mean earth-sun distance on a surface perpendicular to the incident radiation is called the solar constant. Evidence indicates that this is a misnomer because the rate is not really constant. Apparently, real variations of at least a few tenths of one percent remain after possible errors of measurement are corrected. Determinations of the solar constant are in the range 1.9-2.0 cal cm^{-2} min^{-1} [4, 5, 6, 7,8]. Further discussion and numerous references are available from Fröhlich [5] and Kessler [4].

During the day, an object at the surface receives energy from direct sunlight and from diffuse radiation which has been scattered by the atmosphere. About 18 percent of total radiation reaching the earth under clear conditions is diffuse sky radiation [2]. Measurements in the hot desert areas of Arabian Peninsula, where average diffuse solar ratiation is 0.175 times the total solar radiation under cloudless skies [9], are consistent with measurements in middle latitudes. The fraction of diffuse radiation under heavily overcast conditions or at high latitudes in winter can approach 100 percent. Multiple reflection between clouds and the surface may also be important if the surface albedo is high. The total radiation may increase by a factor of two or more when the surface is covered with snow and the sky is overcast [10].

Kessler's work [4] contains a good summary of studies of the planetary albedo of the entire earth-atmosphere system. This has been estimated from approximately 28 to 50 percent. Estimates from presatellite years are usually in the range 35-43 percent [2]. More recent studies with satellite data support percentages lower than previously accepted values. These newer investigations indicate that planetary albedos are in the range 28-32 percent. Newer satellite measurements from Ramanathan's [8] study of different geographical regions show that tropical albedos are significantly lower than indirectly determined values from earlier times.

Surface albedo of sand depends upon the moisture content. A representative albedo of wet sand was given as nine percent in earlier references [2, 3]. In one recent study, minimum albedo for wet sandy soil is 8 percent, and it increases to 20 percent as the soil moisture decreases to 20 percent [11]. Albedos of very dry sand in the Sahel usually do not exceed 40 percent [11]. Albedos of crumbled soil in the Sinai may reach 45 percent [12]. According to a very recent evaluation of satellite determinations of surface albedo [13], some computed albedos are too high because of insufficent accuracy in the two-way transmittances. Sample calculations in this new study indicate that one albedo of 38 percent should be 34 percent, and a 37 percent albedo has been recomputed as 29 percent.

Moisture also influences albedo of other kinds of soil. Irrigation at Phoenix, Arizona, and at Sidney, Montana, influences the albedo of loam, considerably [14]. When albedos are normalized to remove zenith effects, means increase from 14 to 29 percent as mean volumetric water content, in the uppermost layer of loam, decreases from 30 to 7 percent. Normalized albedo is linearly related to moisture at the surface over the range 0 to 18 percent volumetric water content of the Avondale loam at Phoenix in all seasons [15].

Increased reflection of energy from a soil surface, as it dries, does not necessarily mean that the temperature decreases. More energy is available for heating at the surface when albedo is low, but latent heat of vaporization also affects temperature when moisture is available. Wet sand dries much more rapidly than wet loam or clay [16, 17]. During a period in which soil is drying out, minimum temperatures decrease slightly from night to night, and midday maxima increase considerably from one day to the next.

Surface albedos can be drastically altered by the growth of vegetation. Albedos of adjacent plots of land are often quite different. Albedos reach 45 percent in Otterman's [12] measurements of the Sinai with crumbled soil. Albedos are 28 percent in the adjacent Negev where small bushes dot the landscape and debris from dead plants remains undisturbed on the ground. Similar differences exist at the Afghanistan-Soviet border.

The differences in albedo between bare soil and areas with vegetation are associated with differences in temperature. Otterman and Tucker's [18] measurements in the dry season to compare a fenced off area where vegetation existed to the surrounding Sinai showed a hotter vegetation area most of the time during daylight. The maximum difference of temperature was 2.5°K. Because of the lower albedo in an area with vegetation, more energy is available for heating. The moisture is low in the Sinai, and vegetation grows only in clumps even when the area is undisturbed. These plants retain water effectively. Evaporation and evapotranspiration are not important in the dry season in the Sinai. Measurements show that both the clumps of plants and the bare soil have higher temperatures than the air during daytime [19]. The temperature of the bare soil between the plants is warmer than the plants except for a short while after sunset. The soil may be 6°C warmer than the plant surfaces in the afternoon.

Areas with higher albedos than nearby areas with lower albedos do not always have lower temperatures in every location in the world. This is not even true throughout the tropics. In non-arid regions evapotranspiration is strong, and a large portion of incident solar energy becomes latent heat. Measurements in Senegal in the sub-Saharan region of Africa show that very sparse vegetation has a higher albedo than very dense vegetation throughout the year [20]. Winter is the dry season in Senegal. The albedos and ground temperatures for 30 January 1982 were 33 percent and 318.4°K for the region with sparsest vegetation and 16 percent and 316.4°K for the region with densest vegetation. The rainy season in Senegal is late summer and early fall. Albedos and temperatures for 25 October 1982 were 25 percent and 322.5°K for the area with sparsest vegetation and 18 percent and 307.9°K for the area with the densest vegetation. Since vegetation cannot be dense without some minimum amount of available moisture, evapotranspiration is not totally negligible in any season in the area with densest vegetation. In the wettest season in Senegal, evaporation and evaportranspiration are apparently very important among the dense vegetation.

Grass is a type of vegetation which should be considered because the ideal standard site for a meteorological instrument shelter is over grass. Average surface albedos of a uniform grass cover are similar in widely varying geographical locations. The annual mean albedo over grass for the years 1972-1975 near Hamburg, Federal Republic of Germany, was 22 percent [4]. The mean albedo over grass near Yangambi (0°49'N, 24°29'E), Zaire, was 23 percent during the period July 1957 - December 1959 [4]. Calculations from remote sensing on carefully selected clear days in the years 1972-1978 produced mean monthly surface albedos of 20 percent throughout the year for nonforested park in the environs of Hartford, Connecticut [21].

Most surface types have lower albedos at visible wavelengths (<700 nm) than in the near infrared [22]. Grass and other plants containing chlorophyll show a large dependence on wavelength because of strong chlorophyll absorption bands below 700 nm. Short grass reflects three times as much infrared solar energy as it reflects visible energy. Tropical forests may have near infrared reflections five times as large as visible reflections. Bare soils usually reflect about twice as much near infrared energy as visible energy. Snow surfaces are an exception to the usual situation. The reflection of near-infrared energy, by snow, is only about half as much as the reflection of visible energy.

B. Sky Radiation

Wavelengths of emission by the earth and its atmosphere are much longer than wavelengths of solar energy because terrestrial temperatures are much lower than solar temperatures. At atmospheric temperatures, most sky radiation is within the range 3-100 μm [23]. Readers interested in the small amount of energy at millimeter and centimeter wavelengths should consult Clark et al. [24] or Smith [25].

The downward flux of longwave radiation at the surface does not really follow the curve of a black body. The atmosphere has strong absorption bands between 8 μm and 14 μm. These are the wavelengths of maximum black-body emissions for temperatures which occur in the lower atmosphere. Conditions in the lowest 1000 m are the most important in determining clear-sky longwave radiation.

In spite of the complexity of the real atmosphere, the downward flux of longwave radiant energy from the sky is often assumed to be proportional to the fourth power of an effective sky temperature [23, 26, 27, 28]. This sky temperature is usually related to some temperature at or near the ground. The proportionality between the two temperatures depends upon a parameter representing water vapor content. Larger water vapor content is associated with higher sky temperature. Only the most sophisticated numerical models integrate detailed vertical variation of absorption and emission. Some models indirectly take into account vertical relationships in the atmosphere. This may be done by developing separate models for day and night, or by dividing the 24 hours into a larger number of time periods [28].

C. Terrestrial Radiation

The upward flux of longwave radiation from natural surfaces is usually approximated by the black-body emission from the surface. The magnitude of the total upward flux from a black body is proportional to the fourth power of the absolute temperature, and the constant of proportionality is called the Stefan-Boltzmann constant [23]. This constant has a magnitude of $5.7(10^{-12})$ W cm^{-2} ($°K^{-4}$) or $8.2(10^{-11})$ langleys min^{-1} ($°K^{-4}$). This proportional relationship is known as the Stefan-Boltzmann law.

Emittance of a real surface normally shows some deviation from the emittance of an ideal black body. The deviation is expressed in terms of emissivity which is dependent upon temperature and wavelength. The emissivity is defined as the ratio of the emittance of a given surface to the emittance of an ideal black body at the same wavelength and temperature [2]. The emissivity must be within the range zero to unity.

Sometimes investigators consider a mean emissivity in a wavelength interval. This is definded as the integrated emittance in the interval divided by the integrated emittance of a black body in the same interval. Buettner and Kern [29] made laboratory measurements for the wavelength interval 8-12 μm. They called this a window emissivity because it covers a window in water vapor absorption. They found that pure water near 0°C had a window emissivity of 0.993. Thin films of petroleum and corn oil reduced this to 0.972 and 0.966, respectively. Other materials in Buettner and Kern's study were tested at temperatures near 20°C. Window emissivities were 0.966 for dry concrete walkways and 0.956 for asphalt paving. Window emissivity of dry sand composed mainly ot quartz was 0.914 for large grains and 0.928 for small grains.

Buettner and Kern [29] found much lower mean emissivities in the 8-12 μm window for polished samples of minerals containing silicon. These were 0.712 for agate quartz, 0.815 for granite, and 0.870 for feldspar. They compared these measured mean emissivities with integrated values computed from detailed measurements by others. For 293°K, the integrations produced window emissivities of 0.672, 0.780, and 0.819 for quartz, granite, and feldspar, respectively. The detailed earlier laboratory work indicated that variations with temperature were small. Integrated window emissivities of agate quartz decreased from 0.694 at 253°K to 0.664 at 313°K. Changes of emissivity with temperature were smaller for the other minerals. Buettner and Kern also noted that spectral emissivity of these compounds was far from uniform between 8 μm and 12 um. For example, agate quartz has two minimum emissivities in this window: about 0.3 at 8.55 μm and approximately 0.2 at 9.05 μm. These considerations are important in interpreting TIROS satellite window measurements for 8-12 μm. Many newer investigations have data from satellites with channels of data from 10.5 μm to 11.5 μm where quartz has emissivities nearer unity [18].

III. AIR MOTIONS

A. Turbulence and Mean Horizontal Motions

Vertical transfer of sensible heat by turbulent motion is very difficult to measure directly [30]. The vertical heat flux resulting from turbulent eddies may be written as

$$H = \rho C_p \overline{w'T'} \tag{1}$$

where H is heat flux, ρ is air density, C_p is the specific heat at constant pressure, T' is the deviation of temperature from the mean, and w' is the deviation of the vertical wind component from its mean. Direct measurement of turbulent fluctuations is very difficult. Turbulent fluctuations are often assumed to be related to quantities obtained from instruments with slower response times. An assumption that flux of heat and momentum are related is also made. Typical formulae are similar to the following one from Smith et al. [31]

$$H = \rho C_p C_D U(T_s - T_A). \tag{2}$$

They measured U, the horizontal wind speed, at 4.0 m and T_A, the air temperature, at 3.0 m. The skin temperature, T_s was determined from the upward flux of infrared energy according to the Stefan-Boltzmann law discussed in section II,C. The drag coefficient, C_D, is a function of the bulk Richardson number.

If the temperature of the underlying surface changes along the path of moving air, the effects of mean horizontal advection of energy may also be significant.

B. Mean Vertical Motion

When a parcel of air moves from one level to another, its temperature changes as it expands or becomes compressed as a result of the pressure change. Superadiabatic lapse rates of temperature do not normally occur above 100 m, and they are not common except in the lowest few meters. Therefore, large-scale average sinking motion will be associated with an increase in temperature unless net radiative cooling is large enough to counterbalance it.

Descending motion over a large area is usually called subsidence, and this may be a significant factor in increasing temperatures. Much of the Sahara and part of the Arabian Peninsula do not have the annual net ratiative heating which occurs in most of the tropics [8]. High albedo of desert sand and clear skies permit reflected solar energy and radiated longwave energy to leave the atmosphere at rates which produce negative annual net radiation balance in the desert regions. Subsidence not only explains many of the high temperatures in the Arabian Peninsula [32], but also it is sometimes important in the American southwest [33].

IV. CONDUCTION

The vertical heat flux in the ground equals the product of the thermal conductivity of the soil and the vertical temperature gradient in the soil. The conductivity is determined by multiplying the density, specific heat, and thermal diffusivity of the soil. Griffiths [34] has listed thermal diffusivities in the range 0.004-0.010 cm^2 sec^{-1} for wet sand 0.002-0.005 cm^2 sec^{-1} for dry sand. The diurnal temperature wave does not penetrate very deep in extremely arid regions. It was barely noticeable at a depth of only 35 cm in a study at Sharouwrah in Empty Quarter in the Arabian desert [35]. The diurnal cycle in this desert is undetectable at 50 cm at Jeddah, Saudi Arabia, and this was assumed to be true at Sharouwrah too. Skin temperatures were not measured in this study. It is known that midday skin temperatures were very high. The strong lapse rates produced so much instability that overturning of the air in the lowest few centimeters raised a shallow veil of sand. On some days, at a depth of only 2 cm, the diurnal range was approximately 47°C. Mean diurnal range in June 1981 was about 35°C at 2 cm and 4°C at a depth of 20 cm.

V. REGIONS WITH VERY HIGH TEMPERATURES

A. Shelter Temperatures

Surface temperatures in standard weather data are measured between 1 m and 2 m above the ground. In the United States, the thermometers are in white instrument shelters which have louvered sides to provide adequate ventilation [36]. The shelters are mounted on stands which are 4 feet (1.22 m) above the ground, and the thermometers are located at central points within the shelters. This places the bottom of the thermometers 54 inches (1.37 m) above the ground. The shelters should be placed near the center of a plot covered with short grass. The grass plot should be at least 20 feet by 20 feet. An ideal location would have a much larger area without trees, buildings, or large surfaces of concrete.

According to Bennett et al. [37], the average daily maximum temperature in the warmest month is greater than or equal to 110°F (43.3°C) in the following locations: (a) a large portion of northwestern Africa; (b) much of the Arabian Peninsula; (c) part of Pakistan; and (d) a small part of the southwestern United States. Plate I of Bennett et al. [37] even shows an average daily maximum greater than or equal to 115°F (46.1°C) in a region around the point at 5°W and 25°N where Algeria, Mauritania, and Mali meet. Here, more than half of all hours in the warmest month have temperatures greater than or equal to 100°F (37.8°C). This same region is found to be the hottest in the later report by Ohman [38].

Records for more than twenty years exist for a few stations along the periphery of the hottest region in northwestern Africa (Meteorological Office of Great Britain, [39]). Average daily maximum temperatures occur in July at these stations, but absolute maxima may occur in some other month. Aoulef (27°04'N, 01°06'E, 289 m) has an average daily maximum temperature of 45.1°C (113°F) for July. The absolute maximum at this station for 1941-1961 is 49.9°C (122°F), and it is for July. Three nearby stations also have very high average daily maximum temperatures during July: Adrar (27°53'N, 00°17'W, 263 m) with 44.8°C (113°C); Timimoun (29°15'N, 00°17'E, 312 m) with 44.7°C (112°F); and In Salah (27°12'N, 02°28'E, 293 m) with 44.5°C (112°F). The absolute maximum at Adrar is 49.4°C (121°F) for 1941-1969, and it occurs in July. The absolute maximum at Timimoun for 1941-1969 is 50.7°C (123°F), and it occurs in August. At In Salah the absolute maximum is 51.2°C (124°F) for 1941-1970, and this maximum is from September. A little farther away from the region of the highest average daily maximum temperatures, Ouargla (31°54'N, 05°20'N, 139 m), Algeria, has 52.7°C (127°F) for a July and annual absolute maximum. Timbouctou (16°46'N, 03°01'E, 269 m) in Mali has recorded an even higher absolute maximum temperature, 54.5°C (130°F), in May.

There is not total agreement on the absolute maximum temperature for the entire earth (Riordan and Bourget, [40]). A temperature of 58°C (136°F) at El Azizia (32°32'N, 13°01'E, 112 m), Libya, on 13 September 1922 is often accepted as the highest. Questions about the exposure and the accuracy of the instrument have caused some investigators to believe that a more realistic record high for El Azizia is 56C (133°F). Such really high temperatures do not recur frequently. The maximum temperature at El Azizia during the later period 1955-1966 is only 47.6°C (118°F) according to the Meteorological Office of Great Britian [39].

The most widely accepted maximum temperature for the western hemisphere is 134°F (56.7°C) on 10 July 1913 at Death Valley (37°N, 117°W) below sea level in California. This temperature is the official record of the United States Weather Bureau.

Additional information on durations of high temperatures as well as maximum temperatures and temperatures exceeded one and five percent of the time has been compiled by Billions [41]. All observations were carefully checked, and most were within the time period 1955-1969. The highest temperature from this study of hot, dry regions throughout the world is 123°F (50.6°C) at Jacobabad, Pakistan, in May.

Twelve of 84 stations examined by Billions had temperatures greater than or equal to 115°F (46.1°C) at least one percent of the time during at least one month. These stations are in Saudi Arabia, Iran, Iraq, Algeria, Pakistan, and the Sudan. The highest temperature which was equaled or exceeded one percent of the time was 119°F (48.3°C) for July at Qaisumah in Saudi Arabia. Table 1 extracts temperatures equaled or exceeded one percent of the time at 34 hottest stations examined by Billions [41].

Table 2 lists the temperatures equaled or exceeded five percent of the time at these stations. Seven had temperatures greater than or equal to 114°F (45.6°C) five percent of the time during at least one month. These stations are in Saudi Arabia, Iran, Algeria, and Pakistan. The highest temperature which was equaled or exceeded five percent of the time was 116°F (46.7°C) for July at two stations in Saudi Arabia.

Durations for temperature thresholds greater than about 100°F (37.8°C) are less than 24 hours because of the large diurnal changes. Three-hourly seasonal means and standard deviations of temperature and dew point at Dhahran (26°16'N, 50°10'E, 23 m), Saudi Arabia, during the years 1973-1981 are contained in Table 3. Table 4 gives this information for the much drier station of Baghdad (33°15'N, 44°14'E, 34 m), Iraq, for the years 1973-1980. This information is taken from Stewart et al. [42]. The average diurnal range in summer was 17°C at Baghdad and 11°C at Dhahran. Gringorten and Sissenwine [43] examined data from July at Yuma, Arizona, and found that the diurnal range was approximately 15°C for all days and for very hot days.

The Aerophysics Group here in Research Directorate has also studied data from Yuma (32°39'N, 114°37'W, 63 m elevation). Hourly surface weather data were obtained on magnetic tape from the United States Air Force Environmental Technical Applications Center (ETAC). The period of record was 1 January 1973 to 31 December 1986, and it was found that approximately three percent of these observations were missing or obviously erroneous. When there was doubt, it was usually assumed that an observation was correct.

The three percent (of the 122712 observation times) with missing or erroneous data were replaced by interpolation. Simple linear interpolation was used if the gap consisted of only one or two hours. Values in longer gaps were filled in so that a realistic diurnal variation existed in relation to the observed data during the day. Only one entire day was missing, and an interpolation was made between the preceding and following days.

Tables 5-16 were obtained from the serially completed tape for the months January through December at Yuma, Arizona. Each table contains hourly maximum, mean, and minimum temperatures and dew points in degree Kelvin. Times are Greenwich Mean Times (GMT).

Table 17 contains data from the latest Handbook of Geophysics and the Space Environment [44]. This is representative of a five-day period where the temperature reaches 322°K in the afternoon of the middle day. The diurnal range here is 17°C on the hottest day.

B. Ground Temperatures

There is no general agreement concerning the highest possible temperature of the ground or of an object on the surface. According to Ghiocel and Lungu [45], a black surface under direct solar radiation can reach 90°C in a hot, dry climate and 80°C in a hot, humid climate. Dubief [46] found that the temperature of the west surface of a tin box painted black and placed on the sandy area reached a temperature of 84°C during the afternoon of 9 July 1931 at Touggourt. Interior temperature in the box reached 66°C, and the highest ambient air temperature was 47.2°C on 9 July 1931 at Touggourt. The highest soil surface temperature in Chang's [47] extensive survey of published results is the 82°C (180°F) from a report in 1882 on measurements at 4°S in Loango, French Equatorial Africa. Other high temperatures from Chang's survey are 75°C (167°F) at Poona, India, reported in 1940 and 74°C (165°F) at Tucson, Arizona, according to a report in 1939.

Griffiths and Soliman's [48] discussion of soil surface temperatures at Tamanrasset, Algeria, during the eight years 1933-1940 indicates that maxima in August were 69.5°C (157°F). Daytime maxima were normally above 65°C (149°F) from May to September.

Very high ground surface temperatures have been measured in Saudi Arabia. Griffiths' [49] measurements in the southern part of the Arabian Peninsula include temperatures in the range 160°F (71.1°C) to 170°F (76.7°C). Much more recent measurements (Smith, [35]) in 1981 also show that the desert sand becomes very hot. Mean maximum temperatures at a depth of 2 cm for the month of June 1981 were near 60°C (140°F), and mean minima were near 25°C (77°F). During the very hot three days, 30 May through 1 June 1981, the average maximum ground temperature was near 70°C (158°F), and the average minimum was about 22°C (71.6°F) at the 2-cm depth of measurement. Smith assumed that the actual diurnal variation of the boundary between air and earth was more than 50°C. Another study on the Arabian Peninsula (Blake et al., [32]) used remote sensing to determine that the soil surface heated very fast when the sun rose. Within only 45 minutes, it changed from 24°C to 48°C. This is an increase of ½°C per minute.

Oliver [50] measured temperatures just below the surface at 0800, 1400, and 2000 hours local time at Khartoum (15°37'N, 32°33'E) during 1958 - 1962. The absolute maximum, 73.0°C, at 1 cm depth occurred in April at 1400 hours. The mean temperature at 1 cm during April was 65.3°C for the five year period. Mean temperatures at 1 cm were 60.0°C, 64.5°C, and 63.2°C during March, May, and June, respectively. A rainy season in July at Khartoum caused its mean temperature at 1 cm to be only 54.4°C. Monthly means at 2.5 cm at 1400 hours were 6 to 10°C lower than the means at 1 cm.

In a study by Williams [33] at Yuma Proving Ground, most afternoon soil surface temperatures did not get higher than 150°F (65.6°C), and the maximum was approximately 155°F (68.3°C). Minimum ground temperatures on these hot days were typically 75°F to 85°F.

Gupta and Gupta [51] examined the effect of soil management practices on the diurnal variation of soil temperature at Jodhpur, India. The soil was 85.2 percent sand, 4.8 percent silt, and 9.9 percent clay. Soils were irrigated at the beginning of the study. Pulverized soil which was also mulched had maximum afternoon temperatures in the range 4-10°C lower than soils which were only pulverized. Afternoon surface temperature differences between these mulched soils and compacted soils were the same order of magnitude.

Motors and tires of moving vehicles can become even hotter than stationary items [52]. Temperatures of engine oil can exceed 225°F (107.2°C) during operation. The interior of rubber tires can be heated above 250°F (121°C) by concentration of energy from ambient heat, radiation, and friction.

C. Vertical Temperature Gradients

Temperature gradients at midday on hot days are largest very near the surface [53, 54]. Not only are vertical gradients larger near the surface, but so are horizontal gradients associated with changes in the underlying surface (Culpepper, [55]). The limited information available for the very hottest regions of the earth is consistent with this generalization.

Deacon's [23] reference book states generally that desert surfaces with light winds and high sun can be 25-30°C warmer than air at heights of 1 to 2m. This is consistent with Rumney's [56] text which quotes extreme examples where desert surface temperatures were 48°F and 55°F higher than air temperatures at a few feet. Williams [33] measurements at Yuma contain differences between afternoon ground and shelter temperatures in the range 19°F to 46°F, and thus the largest differences were in the range of very high differences suggested by Deacon.

Vehrencamp [57] investigated heat transfer in a dry lake bed at El Mirage in California. The surface was exceptionally hard-packed and level. On a typical day, 11 June 1950, the difference between the temperature at the surface and at 2 m reached 28°C near the middle of the day. The difference was $\geq$20°C from 0900 to 1400 Pacific Standard Time.

The largest gradients are in the lowest 0.1 m or less. Williams' data from Yuma show that the difference between the ground surface and 2.5 cm can be 25-30°F at midday. Griffiths [49] gives one extreme example where the temperature changes from 170°F to 120°F in the lowest 2 inches in the southern Arabian Peninsula. Griffiths [34] discusses a change of 36°F in the lowest centimeter at an undisclosed location.

D. Wind

Gringorten et al. [44] discussed maximum steady wind speeds likely to be encountered at various temperatures based on anemometer data from 12 m to 30 m above the ground in the United States. They recommended design criteria with a maximum speed of 5 m/sec for a temperature of 319°K. This increased linearly to approximately 29 m/sec at 300°K and remained constant from 300°K to 264°K. Winds from hurricanes and tornadoes were not included in the data. Gringorten et al. also pointed out that these recommendations are not valid in mountainous areas and Death Valley.

E. Sky Temperatures

The equivalent radiative temperature for clear skies depends upon the air temperature and the amount of water vapor in the air. Values of these parameters at or near the level of the instrument shelter are usually used to determine the sky temperature. One frequently used formula [28] for the sky temperature T_{SKY} is

$$T_{SKY} = (0.8004 + 0.00396t_d)^{0.25}T_A \qquad (3)$$

where T_A is air temperature in degrees Kelvin and t_d is the dew point in degrees Celsius.

Because the factor containing the dew point has an exponent of 0.25, a large change in dew point is necessary to produce a large change in sky temperature. For a dew point of 0°C, the air temperature is multiplied by 0.9459 to obtain the sky temperature. For a dew point of 30°C, the factor is 0.9792. It follows that air temperature is more crucial than dew point in determining sky temperature.

Mean dew points at Reggan and In Salah are available in World Wide Air Field Summaries [58]. Mean dew points in July, the hottest month at both stations, are 49°F for In Salah and 36°F for Reggan.

Table 3 shows that mean dew points at Dhahran are at least 14°C throughout the day in summer and fall. There are significant diurnal variations. Largest mean hourly dew points in summer and fall at Dhahran are near 20°C and occur in early evening. Earlier work [42] shows that maximum dew points at Dhahran are above 30°C (86°F).

VI. CONCLUSIONS

The diurnal cycle of ambient air temperature on the hottest day of a five-day cycle in Table 17 is representative of very hot days from the various data which were examined. It is essentially the same as the diurnal temperature variation in Table 2.2 of AR 70-38 (1 August 1979).

The AR 70-38 assumes that dew points are no higher than 24°F (-4.4°C) at any time during the day in the very hottest regions. It points out that stations in narrow strips along the coast of the Persian Gulf and the Red Sea are both hot and humid. The present study found that some other hot stations have higher dew points than in the AR 70-38. For example, one percent of the time in July temperatures at Reggan exceed 117°F (47.2°C) according to Billions [41]. The mean dew point at Reggan in July is 36°F (2.2°C) according to World Wide Airfield Summaries [58]. At Jacobabad, Pakistan, the one percent temperature is 118°F in May and June [41]. During these months, the mean dew points are 52°F (11.1°C) and 71°F (21.7°C) at Jacobabad [59].

Several investigators have shown that when the sun is high in the sky on a clear day in hot regions, the ground is often 25-30°C warmer than meterological shelter temperatures. The maximum ground surface temperature is 145°F (63°C) accordng to the statement on page 2-3 of AR 70-38 (1 August 1979). This is too low. Ground temperatures above 150°F have been measured at Yuma. Other stations are hotter. Many studies include ground temperatures ≥70°C at hotter sites.

TABLE 1. Temperature (°F) Equaled or Exceeded One Percent of Time [41].

Station	Apr	May	Jun	Jul	Aug	Sep	Oct
Yuma, Arizona	98	103	112	112	109	108	100
Needles, California	97	103	111	113	111	109	98
Multan, Pakistan	107	115	114	111	106	104	99
Jacobabad, Pakistan	109	118	118	112	107	104	100
Khanpur, Pakistan	108	115	114	111	108	104	100
Chhor, Pakistan	110	113	111	105	102	104	102
Ouargla, Algeria	93	104	109	111	112	105	103
Hassi Messaoud, Algeria	96	106	110	111	114	108	94
In Salah, Algeria	101	108	113	115	114	111	100
Adrar, Algeria	99	106	113	116	115	112	97
Reggan, Algeria	100	107	112	117	113	112	99
Timbuktu, Mali	110	113	114	108	102	108	108
Fort Trinquet, Mauritania	98	104	113	111	110	108	98
Fort Gouraud, Mauritania	100	108	110	112	112	108	100
Atar, Mauritania	103	109	110	112	111	107	102
Kiffa, Mauritania	110	112	112	106	104	106	106
Ghadames, Libya	95	104	109	112	109	105	95
Luxor, UAR	106	109	114	108	109	106	100
Aswan, UAR	106	110	114	110	110	109	106
Siwa, UAR	106	108	113	106	106	104	103
Dakhla, UAR	107	108	114	109	110	106	106
Kassala, Sudan	114	115	110	104	101	106	106
Karima, Sudan	112	114	116	112	112	112	109
Atbara, Sudan	110	112	112	110	108	108	106
Khartoum, Sudan	110	112	110	107	104	106	106
Faya Largeau, Chad	109	111	112	109	108	107	104
Baghdad, Iraq	93	106	111	115	115	109	100
Nasiriya, Iraq	96	107	113	114	116	113	102
Nukhaib, Iraq	100	104	107	112	113	110	96
Qaisumah, Saudi Arabia	102	110	115	119	116	110	102
Nariya, Saudi Arabia	102	116	118	118	117	115	108
Masjed-Soleyman, Iran	93	107	115	117	115	108	100
Abadan, Iran	96	110	115	117	116	113	104
Jodhpur, India	108	112	110	104	100	102	101

TABLE 2. Temperature (°F) Equaled or Exceeded Five Percent of Time [41].

Station	Apr	May	Jun	Jul	Aug	Sep	Oct
Yuma, Arizona	92	98	108	109	105	105	95
Needles, California	90	98	106	109	108	104	94
Multan, Pakistan	102	109	111	106	103	101	96
Jacobabad, Pakistan	105	114	114	108	104	101	98
Khanpur, Pakistan	105	112	112	108	105	102	98
Chhor, Pakistan	106	110	107	100	98	99	98
Ouargla, Algeria	89	98	105	108	108	100	88
Hassi Messaoud, Algeria	90	99	107	108	109	101	89
In Salah, Algeria	97	104	110	112	112	108	96
Adrar, Algeria	95	103	110	114	112	109	95
Reggan, Algeria	94	104	111	114	112	107	96
Timbuktu, Mali	107	109	109	104	99	103	104
Fort Trinquet, Mauritania	93	100	104	109	108	104	93
Fort Gouraud, Mauritania	98	104	107	110	108	105	98
Atar, Mauritania	100	105	108	109	108	104	100
Kiffa, Mauritania	108	109	109	102	99	101	104
Ghadames, Libya	91	100	105	108	106	100	90
Luxor, UAR	99	104	109	105	106	103	96
Aswan, UAR	100	105	109	106	107	104	100
Siwa, UAR	91	98	104	101	101	96	91
Dakhla, UAR	98	100	106	102	102	99	98
Kassala, Sudan	108	109	105	98	95	99	100
Karima, Sudan	106	109	112	108	107	108	104
Atbara, Sudan	106	109	110	106	105	106	103
Khartoum, Sudan	107	109	107	104	102	103	103
Faya Largeau, Chad	107	108	109	107	106	105	102
Baghdad, Iraq	88	101	108	111	110	106	95
Nasiriya, Iraq	90	101	108	110	112	108	97
Nukhaib, Iraq	89	100	107	110	109	106	92
Qaisumah, Saudi Arabia	95	107	110	116	104	108	99
Nariya, Saudi Arabia	96	109	114	116	115	114	103
Masjed-Soleyman, Iran	92	103	113	114	112	105	96
Abadan, Iran	91	106	111	114	113	109	100
Jodhpur, India	105	110	107	100	96	98	98

TABLE 3. Diurnal Variation of Means and Standard Deviations of Temperature (T) and Dew Point (TD) in Degrees Celsius at Dhahran (26°16'N, 50°10'E, 23m), Saudi Arabia, for the Period 1973-1981.

Local Time	Variable	Season: Winter	Spring	Summer	Fall
0000	Mean T	14.8	22.5	30.8	24.2
	σ(T)	3.2	5.1	2.7	4.5
	Mean TD	11.4	15.0	19.9	19.4
	σ(TD)	4.1	4.7	6.1	5.4
0300	Mean T	13.4	20.8	29.5	22.7
	σ(T)	3.6	4.9	2.6	4.5
	Mean TD	10.6	14.4	17.9	18.3
	σ(TD)	4.5	4.8	6.6	5.8
0600	Mean T	12.9	20.7	29.3	21.8
	σ(T)	3.6	5.1	2.5	4.6
	Mean TD	10.0	13.9	15.9	16.4
	σ(TD)	4.6	5.0	7.4	6.4
0900	Mean T	15.8	26.6	36.3	27.9
	σ(T)	3.4	5.8	2.0	5.3
	Mean TD	10.5	13.0	14.5	15.8
	σ(TD)	4.8	5.1	7.2	6.9
1200	Mean T	20.2	30.2	40.2	32.6
	σ(T)	3.4	6.0	2.8	5.3
	Mean TD	10.4	11.5	14.0	14.4
	σ(TD)	4.6	5.5	6.8	6.0
1500	Mean T	20.9	30.0	39.7	32.6
	σ(T)	3.2	5.8	2.2	5.0
	Mean TD	10.1	11.8	15.2	15.8
	σ(TD)	4.6	5.7	6.4	5.5
1800	Mean T	18.6	27.2	36.5	29.0
	σ(T)	2.9	5.4	2.1	4.9
	Mean TD	11.6	13.7	18.0	19.0
	σ(TD)	4.1	5.1	6.1	5.0
2100	Mean T	16.2	24.3	32.8	26.1
	σ(T)	2.8	4.9	2.0	4.5
	Mean TD	11.9	15.1	20.5	20.2
	σ(TD)	4.0	4.7	6.1	5.0

TABLE 4. Diurnal Variation of Means and Standard Deviations of Temperature (T) and Dew Point (TD) in Degrees Celsius at Baghdad (33°15'N, 44°14'E, 34m), Iraq, for the Period 1973-1980.

Local Time	Variable	Season: Winter	Spring	Summer	Fall
0000	Mean T	8.4	19.5	29.1	19.1
	σ(T)	4.1	5.7	3.3	6.9
	Mean TD	4.2	7.1	8.0	6.2
	σ(TD)	4.1	4.5	3.5	4.4
0300	Mean T	6.7	16.7	26.1	17.0
	σ(T)	4.1	5.7	3.0	6.5
	Mean TD	3.6	6.8	8.2	5.9
	σ(TD)	4.2	4.3	3.3	4.3
0600	Mean T	6.0	15.6	24.8	15.7
	σ(T)	4.3	5.8	3.1	6.5
	Mean TD	3.0	6.9	8.6	5.4
	σ(TD)	4.8	4.1	3.5	4.3
0900	Mean T	8.4	21.8	33.2	22.6
	σ(T)	3.9	6.6	2.6	7.5
	Mean TD	4.5	7.8	10.0	6.9
	σ(TD)	4.2	4.3	3.9	4.8
1200	Mean T	13.2	26.2	38.5	29.0
	σ(T)	4.2	6.9	3.7	8.2
	Mean TD	5.3	6.4	8.0	6.4
	σ(TD)	4.4	4.9	4.5	4.9
1500	Mean T	16.2	28.7	41.4	32.0
	σ(T)	4.0	6.6	3.3	7.7
	Mean TD	4.7	4.8	5.2	4.9
	σ(TD)	5.1	5.4	4.4	5.1
1800	Mean T	14.4	27.7	40.4	28.9
	σ(T)	4.0	6.7	3.1	8.4
	Mean TD	5.0	4.7	5.4	6.5
	σ(TD)	4.6	5.3	4.1	4.6
2100	Mean T	10.2	21.6	32.2	21.6
	σ(T)	4.1	6.0	3.4	7.2
	Mean TD	4.8	7.2	8.1	6.7
	σ(TD)	4.4	4.3	3.9	4.3

TABLE 5. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for January during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	301.0	292.4	282.6	287.6	273.2	256.2
01	299.3	291.0	280.9	287.6	273.7	257.2
02	296.5	289.3	278.8	288.2	273.9	258.3
03	294.9	288.1	279.3	287.6	273.9	256.1
04	294.9	287.0	277.6	287.6	274.1	257.2
05	293.8	286.1	277.0	287.1	274.3	250.5
06	292.6	285.4	275.9	287.1	274.1	255.5
07	292.6	284.8	274.9	287.1	274.0	254.9
08	292.1	284.3	274.3	287.1	274.0	256.1
09	291.5	283.8	272.7	287.6	273.9	256.1
10	291.0	283.4	273.2	287.6	273.9	256.6
11	290.4	283.0	272.7	287.1	273.7	256.1
12	291.0	282.6	272.2	287.1	273.5	256.1
13	290.4	282.3	271.6	287.1	273.4	256.6
14	291.0	282.2	272.2	287.1	273.2	255.5
15	290.4	282.1	272.7	287.1	273.3	255.5
16	291.5	283.6	274.3	287.1	273.6	257.2
17	292.6	286.0	275.4	287.1	274.2	256.6
18	295.4	288.3	279.8	287.6	274.3	257.2
19	298.2	290.2	281.5	287.6	273.9	257.2
20	299.9	291.4	282.6	288.1	273.7	256.1
21	301.0	292.3	281.5	287.7	273.5	256.6
22	301.0	292.8	282.1	288.2	273.4	256.1
23	301.0	292.9	283.2	287.6	273.2	257.2

TABLE 6. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for February during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	307.6	295.3	280.4	289.3	272.5	255.0
01	306.5	294.4	279.3	289.8	272.8	254.4
02	304.3	292.3	279.3	290.4	273.5	253.3
03	301.5	290.7	278.2	289.9	273.8	252.7
04	299.3	289.4	277.1	289.3	274.3	253.9
05	297.6	288.4	276.0	288.8	274.4	253.9
06	297.1	287.3	275.6	288.8	274.5	251.6
07	295.4	286.6	274.9	288.8	274.6	252.7
08	294.3	286.0	274.3	288.8	274.5	255.0
09	293.2	285.4	274.8	288.2	274.3	252.7
10	293.2	284.9	276.0	288.2	274.2	255.5
11	292.6	284.4	277.1	288.2	274.1	255.0
12	292.1	284.0	275.4	287.6	273.9	253.3
13	291.5	283.7	274.9	288.2	273.7	252.7
14	291.0	283.4	274.9	288.2	273.6	251.6
15	293.2	283.7	274.3	288.2	273.7	252.2
16	294.3	285.9	276.5	288.2	274.1	256.1
17	297.1	288.6	278.2	288.8	274.5	255.0
18	300.4	291.0	280.4	289.3	274.2	255.5
19	303.8	292.3	281.5	288.8	273.8	256.1
20	304.9	294.1	282.1	289.3	273.3	256.1
21	306.5	294.9	282.1	289.9	273.0	256.6
22	307.6	295.5	282.1	289.9	272.8	253.3
23	307.6	295.7	281.5	289.9	272.6	255.5

TABLE 7. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for March during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	310.4	297.2	285.4	288.2	273.4	255.0
01	308.2	296.5	283.8	288.2	273.6	256.3
02	304.9	294.6	282.6	287.6	274.5	255.5
03	302.1	292.8	281.0	288.2	275.0	256.6
04	301.0	291.5	280.4	289.3	275.3	258.3
05	300.4	290.4	279.9	289.3	275.6	258.9
06	298.8	289.5	279.9	289.9	275.8	257.7
07	296.5	288.7	278.8	289.3	275.8	259.4
08	296.5	288.0	278.6	289.3	275.8	257.2
09	294.9	287.4	278.4	288.8	275.7	258.3
10	296.0	286.9	278.2	288.2	275.5	257.2
11	295.4	286.3	278.2	288.2	275.5	257.7
12	294.9	285.9	278.2	287.2	275.4	257.7
13	294.3	285.5	277.1	287.1	275.2	259.4
14	293.8	285.2	277.1	287.1	275.2	258.9
15	294.3	286.5	278.2	287.1	275.5	260.5
16	297.6	289.1	281.0	287.1	275.8	260.5
17	301.0	291.5	282.1	287.1	275.6	258.9
18	304.3	293.5	283.2	287.1	275.2	258.9
19	306.0	295.0	284.3	286.5	274.5	258.9
20	307.6	296.0	286.0	286.5	273.9	258.3
21	308.8	296.8	286.5	286.5	273.7	257.7
22	309.3	297.3	286.5	287.1	273.6	257.1
23	309.9	297.5	286.0	287.1	273.4	256.6

TABLE 8. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for April during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	315.4	301.5	284.3	285.1	273.0	259.2
01	314.9	300.8	285.4	286.0	273.1	259.9
02	313.2	299.0	286.0	286.0	274.0	258.9
03	307.6	296.8	284.3	286.5	274.8	261.0
04	304.9	295.2	283.8	284.3	274.9	256.6
05	305.4	293.8	282.6	285.4	275.1	258.3
06	304.9	292.8	283.2	288.2	275.5	259.4
07	302.6	291.9	281.5	286.0	275.4	255.5
08	302.1	291.1	281.0	287.6	275.5	260.0
09	301.0	290.5	280.4	287.1	275.5	259.4
10	299.3	289.8	279.9	288.2	275.5	258.9
11	298.8	289.2	279.9	287.6	275.6	260.5
12	298.8	288.6	279.3	287.6	275.6	259.2
13	297.1	288.1	279.3	288.2	275.6	259.4
14	297.6	288.4	278.8	287.6	275.8	258.9
15	301.0	290.9	281.5	286.5	276.1	259.[illegible]
16	303.2	293.6	284.3	288.8	276.3	260.0
17	306.0	295.9	285.4	288.2	275.7	259.9
18	308.2	297.7	286.2	287.6	274.8	261.1
19	309.9	299.1	284.9	284.9	274.1	260.0
20	312.6	300.2	286.0	284.3	273.8	261.1
21	314.9	301.1	286.0	283.8	273.6	257.7
22	317.1	301.6	283.8	284.9	273.4	259.3
23	316.0	301.8	283.2	284.3	273.1	260.5

TABLE 9. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for May during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	319.3	306.4	288.8	289.9	275.8	261.1
01	317.1	305.8	292.1	287.6	275.7	261.6
02	316.0	304.3	289.9	287.6	276.5	263.9
03	313.2	301.7	288.8	287.6	277.3	264.4
04	311.0	299.8	287.6	288.8	277.5	262.2
05	310.4	298.3	287.1	289.3	278.0	263.3
06	309.9	297.1	287.1	289.3	278.3	264.4
07	307.6	296.2	286.0	288.8	278.2	264.4
08	307.1	295.4	286.0	288.8	278.2	264.4
09	306.5	294.7	284.3	288.8	278.1	265.5
10	305.4	294.0	284.3	289.3	278.1	266.1
11	304.9	293.3	284.3	290.4	278.4	265.0
12	304.3	292.6	284.2	291.6	278.7	263.9
13	304.3	292.2	283.2	292.1	278.7	265.0
14	303.2	293.4	284.3	292.3	279.2	266.1
15	306.5	295.8	286.5	292.6	279.6	266.6
16	309.9	298.4	288.8	292.1	279.6	265.5
17	313.8	300.5	290.4	290.4	278.7	263.1
18	316.0	302.3	291.5	289.3	278.0	260.2
19	317.6	303.7	292.6	289.3	277.4	261.1
20	319.0	304.9	289.9	288.8	277.0	263.9
21	320.4	305.8	291.5	288.2	276.7	260.5
22	319.9	306.4	292.6	287.1	276.4	261.1
23	320.4	306.7	292.6	287.6	276.1	258.9

TABLE 10. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for June during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	319.3	312.3	299.9	294.3	278.4	264.4
01	318.8	311.8	299.9	293.8	278.5	264.4
02	317.1	310.4	298.2	293.8	279.3	263.2
03	315.4	307.6	296.0	295.4	280.2	265.5
04	311.5	305.4	294.9	294.9	280.2	261.6
05	310.4	303.7	293.8	296.0	280.4	264.4
06	309.9	302.4	292.6	294.9	280.4	263.2
07	308.2	301.3	291.5	294.9	280.3	262.7
08	307.6	300.4	291.0	294.3	280.3	258.9
09	307.1	299.7	290.4	294.9	280.3	254.4
10	306.0	298.9	289.9	294.9	280.3	254.4
11	306.0	298.2	289.9	294.9	280.5	257.2
12	305.1	297.4	288.2	295.4	281.1	264.4
13	305.4	297.0	288.8	294.3	281.4	263.3
14	306.5	298.4	289.9	295.4	281.9	264.4
15	307.6	300.8	292.1	295.4	282.6	266.6
16	311.0	303.4	293.8	294.3	282.4	266.3
17	312.6	305.5	296.0	295.4	281.3	261.6
18	314.3	307.4	296.0	295.4	280.7	262.2
19	316.5	309.0	297.6	296.0	279.9	258.9
20	317.6	310.3	299.3	294.9	279.4	2[illegible].3
21	318.2	311.3	299.9	294.3	279.0	265.0
22	319.9	312.1	299.9	294.3	278.9	263.3
23	319.9	312.5	300.4	296.0	278.8	262.2

TABLE 11. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for July during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	319.3	313.2	298.2	298.2	286.5	266.1
01	318.6	312.6	299.9	297.6	286.6	267.2
02	318.2	311.4	299.9	300.6	287.1	266.6
03	316.0	309.2	298.8	297.6	287.7	267.7
04	313.8	307.4	299.9	297.1	287.8	268.3
05	311.0	306.0	298.8	297.6	288.0	267.2
06	309.9	305.0	297.6	297.1	288.2	263.9
07	311.0	304.2	297.1	297.1	288.2	266.1
08	310.4	303.5	296.0	297.6	288.2	265.5
09	307.6	302.9	294.9	297.1	288.2	262.7
10	307.1	302.4	294.9	297.6	288.3	263.9
11	309.9	301.9	294.9	298.2	288.6	264.4
12	307.6	301.5	294.3	299.3	288.8	266.6
13	308.2	301.2	293.2	298.2	289.0	266.1
14	307.6	301.9	295.4	298.2	289.5	268.3
15	308.8	303.7	297.1	298.2	289.9	270.5
16	312.1	305.7	299.9	297.6	289.8	269.4
17	313.8	307.4	300.4	297.1	289.2	260.0
18	315.4	309.0	298.8	298.2	288.6	261.1
19	317.6	310.4	295.4	297.6	288.1	259.4
20	318.8	311.6	298.8	297.1	287.7	266.1
21	318.8	312.6	300.4	298.2	287.5	262.2
22	318.8	313.1	302.1	297.1	287.1	265.0
23	319.3	313.4	296.5	297.6	286.9	266.1

TABLE 12. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for August during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	320.4	312.8	298.2	301.5	287.1	265.2
01	319.9	312.0	298.8	299.6	287.1	267.2
02	317.6	310.4	296.5	297.1	287.8	267.7
03	315.4	308.4	297.6	297.6	288.1	270.5
04	313.2	306.9	297.1	298.2	288.3	269.4
05	312.1	305.6	297.6	297.6	288.5	268.9
06	310.4	304.6	297.6	299.3	288.9	267.7
07	309.3	303.9	297.1	298.8	289.0	267.7
08	308.8	303.2	296.5	299.3	289.1	269.4
09	308.2	302.7	296.0	298.8	289.2	270.0
10	308.2	302.2	291.0	299.3	289.4	269.4
11	308.2	301.7	293.7	299.3	289.4	268.3
12	308.8	301.3	293.7	299.8	289.7	271.2
13	308.8	300.8	293.7	299.9	289.9	271.6
14	308.8	301.2	294.3	299.9	290.3	270.5
15	309.9	303.0	295.4	299.9	290.6	270.5
16	311.5	305.1	296.2	299.3	290.7	270.0
17	313.8	306.9	297.1	298.2	290.2	271.1
18	316.0	308.6	298.2	300.4	289.4	268.3
19	317.6	310.0	297.1	304.0	288.8	268.9
[illegible]	319.3	311.2	297.1	309.9	288.2	267.7
[illegible]	320.4	312.1	296.0	301.0	287.7	264.4
[illegible]	320.4	312.7	297.1	297.1	287.3	263.8
23	321.0	312.9	297.6	297.6	287.0	263.3

TABLE 13. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for September during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	318.2	310.0	294.3	301.5	284.6	265.5
01	317.1	309.0	293.2	296.0	284.8	265.5
02	315.4	307.0	293.2	297.1	285.3	265.5
03	313.2	305.2	293.2	297.1	285.7	265.5
04	311.5	303.8	292.1	298.8	286.2	265.0
05	311.0	302.7	291.5	297.6	286.4	263.9
06	309.9	301.8	289.9	298.8	286.8	264.4
07	311.0	301.2	289.9	298.2	287.0	265.5
08	308.8	300.4	288.8	298.8	287.1	265.5
09	308.2	299.9	288.8	298.8	287.3	267.1
10	307.1	299.3	288.8	299.3	287.2	267.7
11	306.0	298.8	287.6	298.8	287.4	268.3
12	305.4	298.3	287.6	299.3	287.4	263.9
13	305.4	297.9	287.1	298.8	287.4	266.1
14	306.0	297.9	287.1	298.8	287.4	266.6
15	307.6	299.7	288.2	299.3	287.8	266.6
16	309.9	302.0	291.5	299.3	288.1	267.7
17	313.8	304.1	292.1	298.8	288.0	268.9
18	314.9	305.9	292.6	298.2	287.3	268.3
19	315.4	307.3	291.5	297.6	286.6	266.6
20	317.6	308.5	291.0	297.1	285.9	267.1
21	317.6	309.3	292.6	297.1	285.4	267.7
22	319.3	309.9	294.9	296.0	284.8	267.7
23	318.2	310.0	294.3	296.5	284.5	266.1

TABLE 14. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for October during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	316.0	304.3	290.4	294.3	279.0	263.9
01	313.2	302.7	289.3	294.3	279.4	263.9
02	308.8	300.7	289.3	295.4	280.0	262.7
03	306.5	299.1	289.3	295.4	280.3	262.2
04	305.4	297.8	288.8	296.5	280.5	261.6
05	305.4	296.6	287.6	296.0	280.8	261.1
06	304.9	295.7	287.1	296.5	281.0	261.1
07	302.6	294.9	286.0	297.1	281.0	263.9
08	302.1	294.2	284.3	296.5	281.0	264.4
09	301.5	293.7	284.3	295.4	280.8	264.4
10	301.0	293.1	284.3	296.0	280.7	263.3
11	300.4	292.5	283.8	296.0	280.6	262.2
12	300.4	292.0	282.1	296.0	280.5	262.7
13	300.4	291.6	282.1	296.0	280.4	264.4
14	299.9	291.4	282.6	296.0	280.3	262.7
15	300.4	293.0	283.8	295.4	280.5	263.9
16	303.2	295.7	286.5	297.6	281.2	264.4
17	306.5	298.3	289.3	297.6	281.2	263.9
18	309.9	300.4	291.0	297.1	280.9	263.8
19	311.5	302.0	291.0	295.4	280.5	264.4
20	313.2	303.2	291.0	294.9	280.0	265.0
21	314.9	304.0	291.5	294.9	279.7	265.0
22	316.0	304.4	291.5	295.4	279.3	263.3
23	316.0	304.5	291.0	294.9	278.9	262.7

TABLE 15. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for November during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	306.5	297.2	285.4	288.8	274.0	250.5
01	303.8	295.2	283.2	288.8	274.4	251.6
02	301.5	293.5	281.0	288.8	274.7	250.5
03	299.9	292.1	282.1	288.8	274.8	251.3
04	298.2	291.0	280.4	289.3	275.2	252.2
05	297.6	290.0	279.3	289.3	275.1	251.1
06	296.0	289.1	278.2	289.9	275.2	250.5
07	295.4	288.4	277.6	289.9	275.1	248.9
08	295.4	287.9	278.2	289.3	275.0	248.9
09	294.9	287.4	277.1	289.3	274.8	252.2
10	295.4	286.9	277.6	288.8	274.7	251.6
11	295.4	286.5	277.6	289.3	274.6	251.6
12	294.9	286.0	276.5	289.3	274.3	251.6
13	293.8	285.8	275.4	289.3	274.1	255.0
14	294.3	285.5	276.5	289.3	274.0	254.4
15	294.9	286.1	277.1	289.9	274.1	253.9
16	296.5	288.4	279.3	290.4	274.6	256.1
17	298.2	291.1	282.1	291.0	275.0	253.3
18	302.1	293.4	283.2	290.4	274.9	252.7
19	303.2	295.1	284.3	290.4	274.6	253.3
20	305.4	296.3	285.4	291.0	274.3	253.9
21	306.0	297.1	286.0	290.4	274.0	252.2
22	306.5	297.6	285.4	301.5	273.8	251.6
23	307.1	297.6	285.4	302.1	273.7	250.5

TABLE 16. Hourly Maximum, Mean, and Minimum Temperatures and Dew Points for December during the Years 1973-1986 at Yuma, Arizona.

Hr	Temperature (°K)			Dew Point (°K)		
	Max	Mean	Min	Max	Mean	Min
00	301.5	292.8	281.0	288.2	273.1	253.9
01	298.8	290.9	279.3	288.2	273.4	255.5
02	296.5	289.4	278.2	288.2	273.4	256.6
03	295.4	288.2	277.6	288.2	273.6	257.7
04	297.1	287.2	277.1	288.2	273.8	257.7
05	296.0	286.3	276.5	287.6	273.9	257.7
06	296.0	285.5	275.4	287.6	273.8	258.3
07	294.3	284.9	274.9	288.2	273.7	258.3
08	294.3	284.4	273.8	287.6	273.6	257.7
09	293.2	284.0	271.6	287.6	273.5	257.7
10	291.5	283.5	273.8	287.1	273.4	257.2
11	292.6	283.1	272.2	286.5	273.3	256.6
12	292.1	282.8	273.2	286.0	273.0	256.1
13	292.6	282.5	273.2	286.0	272.8	256.1
14	292.6	282.3	273.2	286.0	272.7	256.1
15	291.0	282.3	272.7	285.4	272.7	255.5
16	294.9	284.0	274.9	288.2	273.0	256.6
17	295.4	286.5	278.2	287.1	273.5	257.7
18	297.1	288.8	278.8	287.6	273.6	253.9
19	299.3	290.7	280.4	287.6	273.4	252.2
20	299.9	292.0	280.4	288.2	273.3	253.9
21	300.4	292.8	280.4	288.2	273.0	252.7
22	301.0	293.3	280.4	288.8	272.9	251.1
23	301.5	293.4	280.4	288.2	272.9	248.3

TABLE 17. Diurnal Cycle of Temperature (°K) for Days when the Maximum Equals or Exceeds 322°K [44].

Hr Local Time	Temperature (°K)		
	Hottest Day	Number of Days Before or After	
		1	2
00	310	309	309
01	308	309	307
02	307	308	307
03	307	307	306
04	306	306	306
05	306	306	305
06	305	305	305
07	306	306	306
08	308	309	308
09	311	311	310
10	314	313	312
11	316	315	314
12	317	317	315
13	320	318	316
14	321	320	317
15	321	320	319
16	322	321	320
17	321	320	319
18	321	319	318
19	319	317	317
20	315	315	314
21	314	313	312
22	312	311	311
23	311	310	310

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